



Could Nano-Structured Materials Enable the Improved Pressure Vessels for Deep Atmospheric Probes?

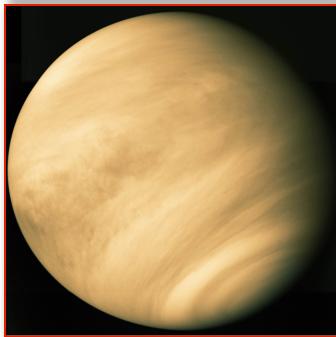


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¹NASA Ames Center for Nanotechnology (NACNT)/UARC

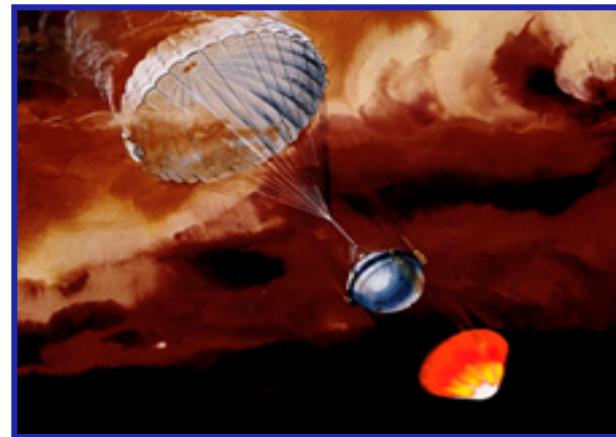
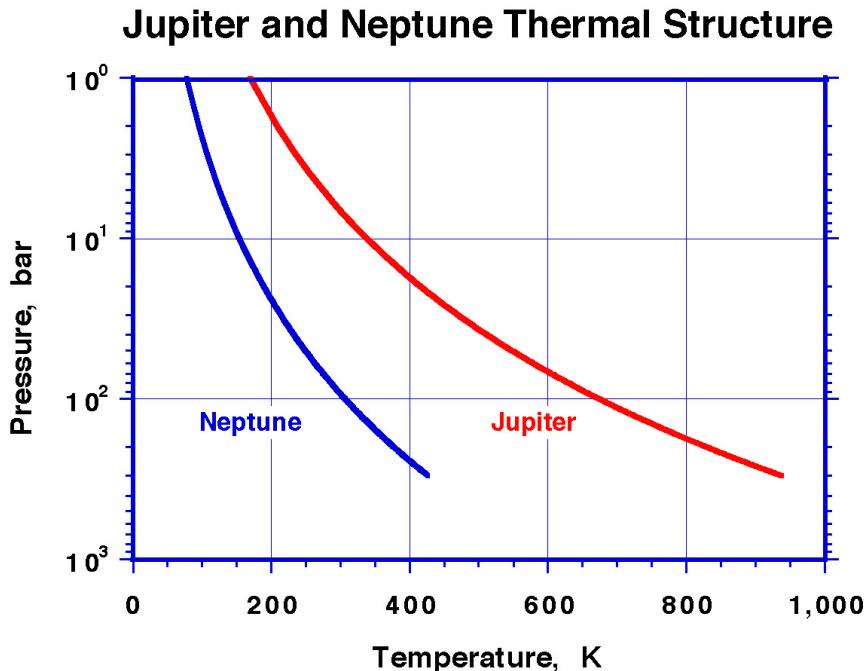
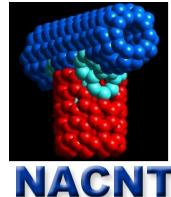
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³The Boeing Corporation, El Segundo Office, CA

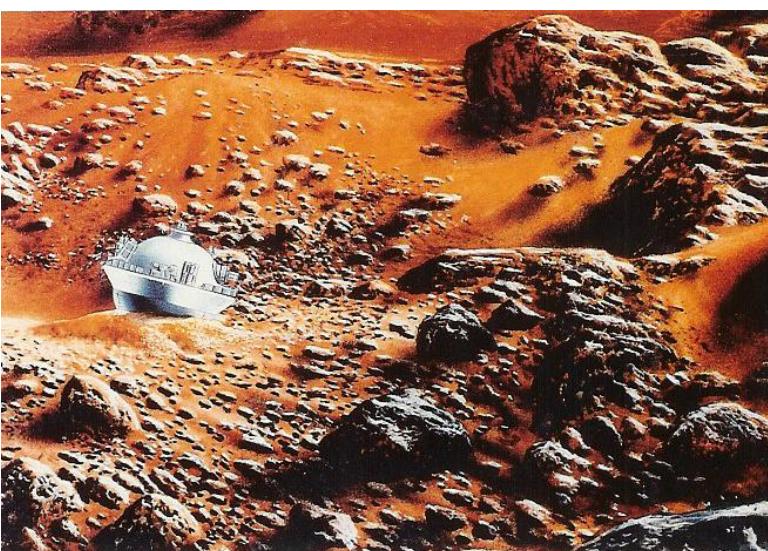




High Temperature/Pressure in Key X-Environments



Pressure - Temperature Atmospheric Profiles Provided² by Rich Young,
NASA Ames Research Center

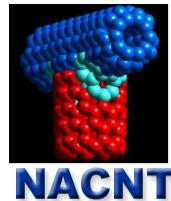


Artists Concept of Pioneer-Venus Small "Day" Probe on Venus ' Surface. T= 740 K, P=96 bars Sealed Vessel with Xenon at 102 Kpa (15 psia).

Operated³ for 68 minutes on Venus' surface - December, 1978



The Case for Use of Nano-Structured Materials Pressure Vessel Design



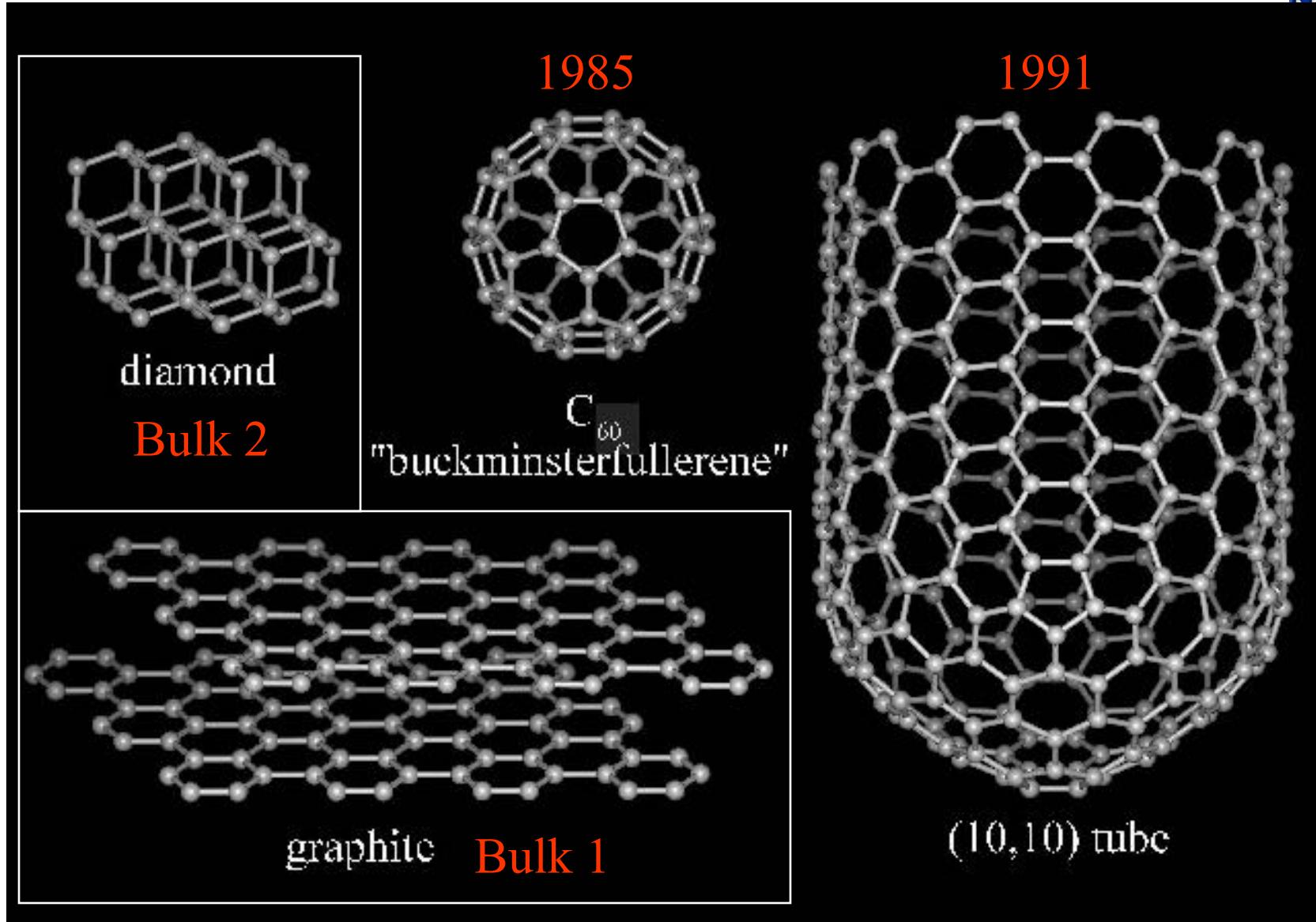
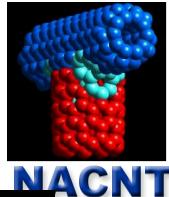
- Pressure vessel structure is a mass driver for probe
- Reduction in structure mass can be used for science

Probe	Pressure Vessel Mass (kg)	Total* Probe Mass (kg)	Pressure Vessel Structure Mass Fraction (%)
Pioneer Venus Large Probe	62	193	32
Pioneer Venus Small Probe	18	61	30

* Excludes deceleration module mass



Carbon based Nanomaterials



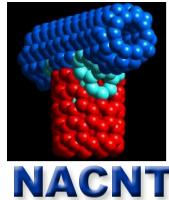
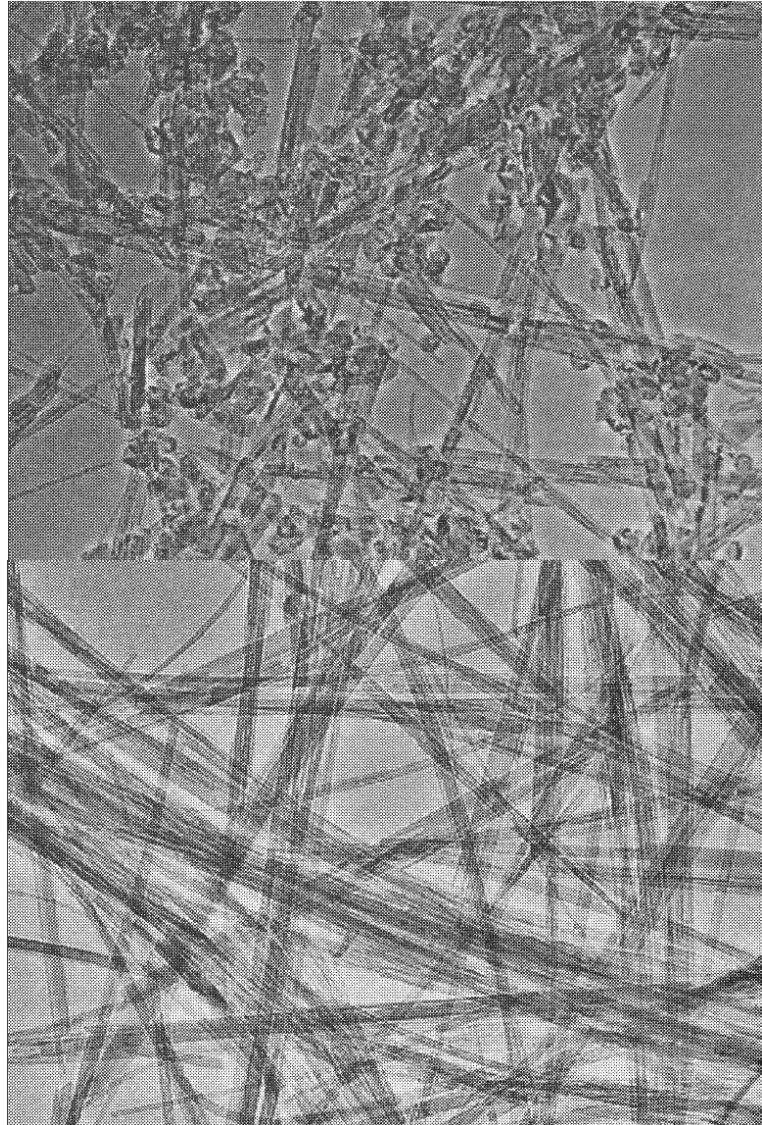


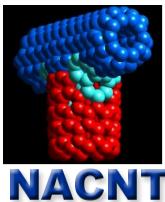
Nanotube production & purification

Micrographs illustrating purification
of multiwalled nanotube sample

MWNTs
 $D = 2.5 - 30 \text{ nm}$

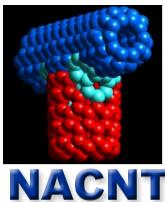
Ebbesen et al.,
Nature 367, 519 (1994)





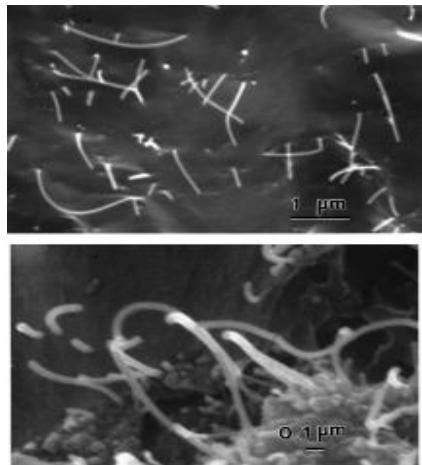
Nanomechanics of Carbon Nanotubes

- *Elastic* properties: $E = \sim 1.2 \text{ TPa}$
 $(E = k/a)$
- *Plastic/Fracture* properties: compression & tension
yield strain $\geq 15 - 20\% (?)$
 - Strain rate?
 - Defects?
 - Mechanisms?
 - Applications?
- *Superstrong Material:* $\sigma_Y = 750 - 1000 \text{ GPa}!$
 - Diamond (50 GPa), WC (6 GPa), Steel (0.5-2 GPa)



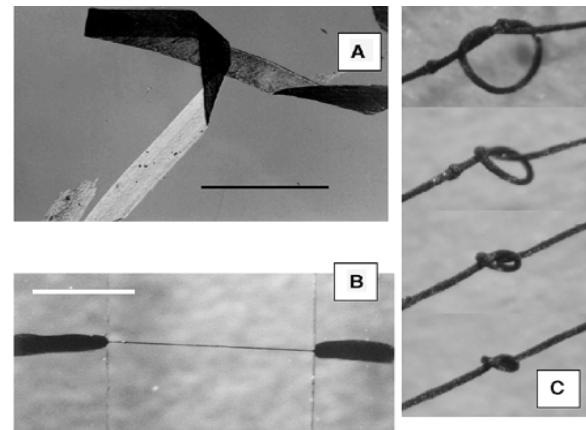
CNT-composites: Example (Polymer)

SEM images of epoxy-CNT composite



(L.S.Schadler et.al., Appl. Phys. Lett. V73 P3842, 1998)

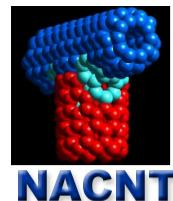
SEM images of polymer (polyvinylacohol) ribbon contained CNT fibers & knotted CNT fibers



(B. Vigolo et.al., Science, V290 P1331, 2000)

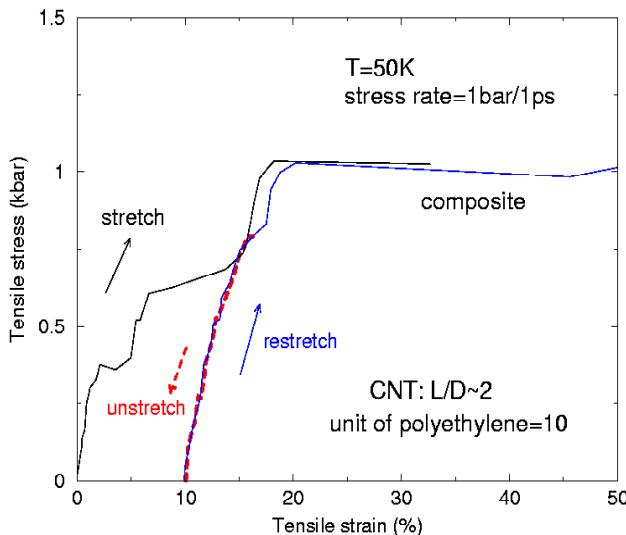


Effect of Loading sequence on Composite with 8% by volume

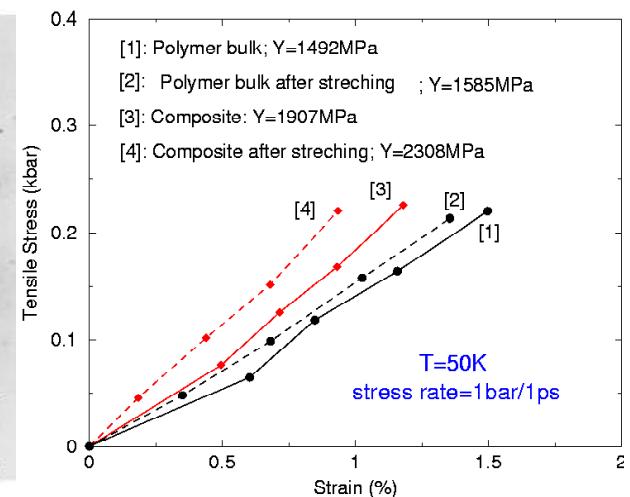
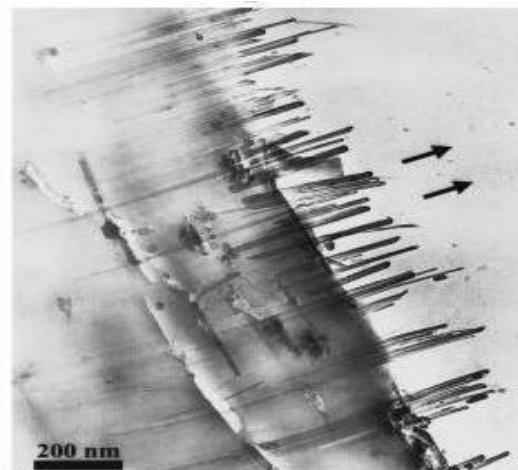


Simulations of CNT-Polyethylene Composites

Work hardening of composite with stretching



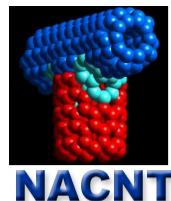
TEM images of alignment of CNTs in a polymer matrix by stretching



- Young's modulus of CNT composites 30% higher than polymer matrix
- Stretching treatments enhance Y by 50%
($L/D \sim 2$, $N_p = 10$)



Models for Particulate Reinforced Composites



Mittal et.al., NASA Technical Report, 1996

Micromechanics Models for Particulate Reinforced Composites

$$\rho_{pc} = V_f \rho_f + (1 - V_f) \rho_m$$

Density of composite

$$E_{pc} = \frac{V_f^{0.67} E_m}{1 - V_f^{0.33} \left(1 - \frac{E_m}{E_f}\right)} + (1 - V_f^{0.67}) E_m$$

Elastic Modulus of Composite

$$K_{pc} = \frac{V_f^{0.67} K_m}{1 - V_f^{0.33} \left(1 - \frac{K_m}{K_f}\right)} + (1 - V_f^{0.67}) K_m$$

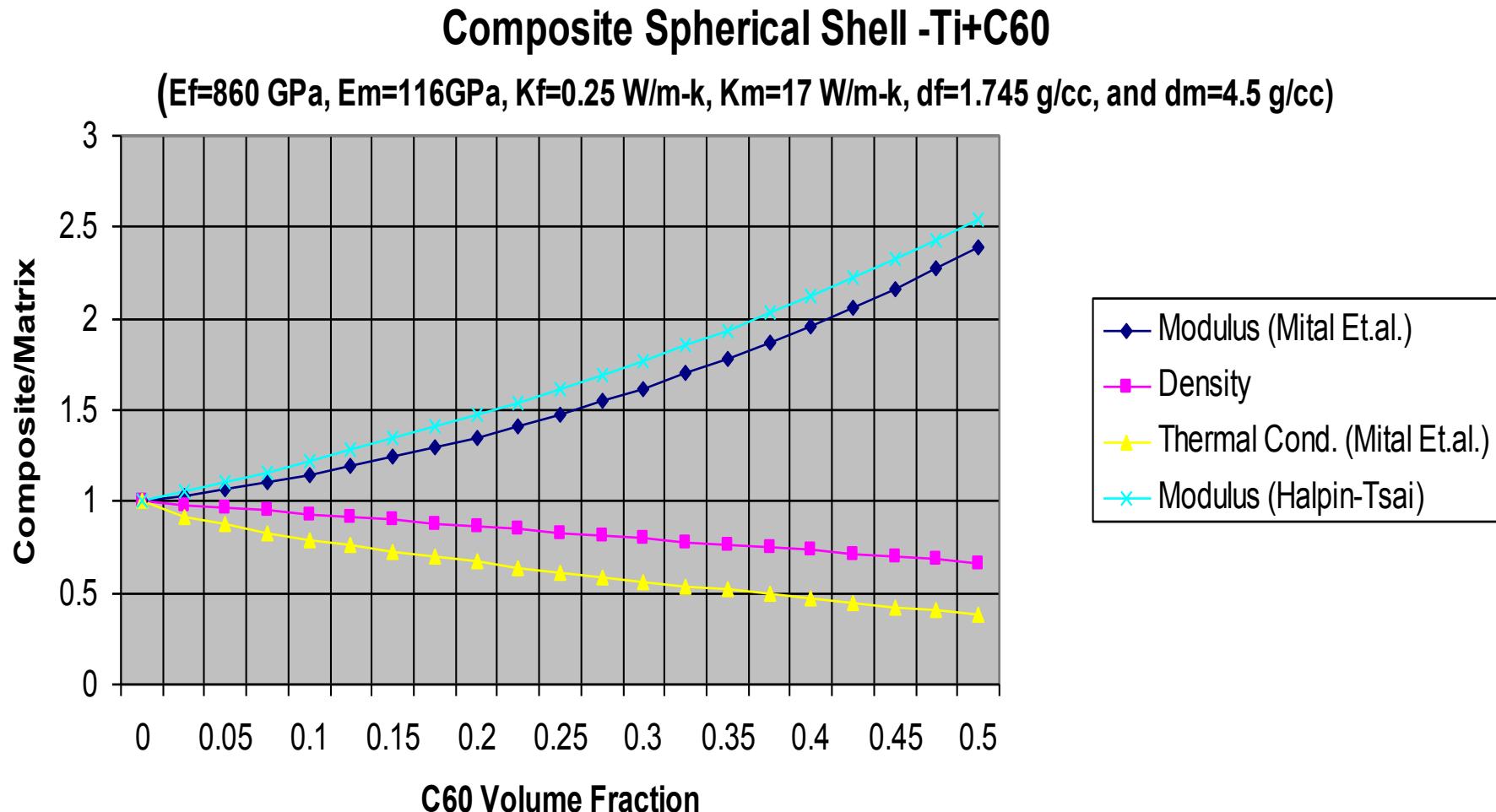
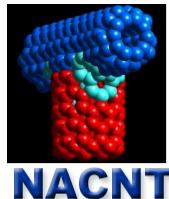
Thermal Conductivity of Composite

Where V_f is volume fraction

Assumption: Ideal Interface – perfect bonding at the interface

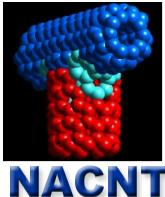


Fullerene/Ti Composite for High Strength-Insulating Layer

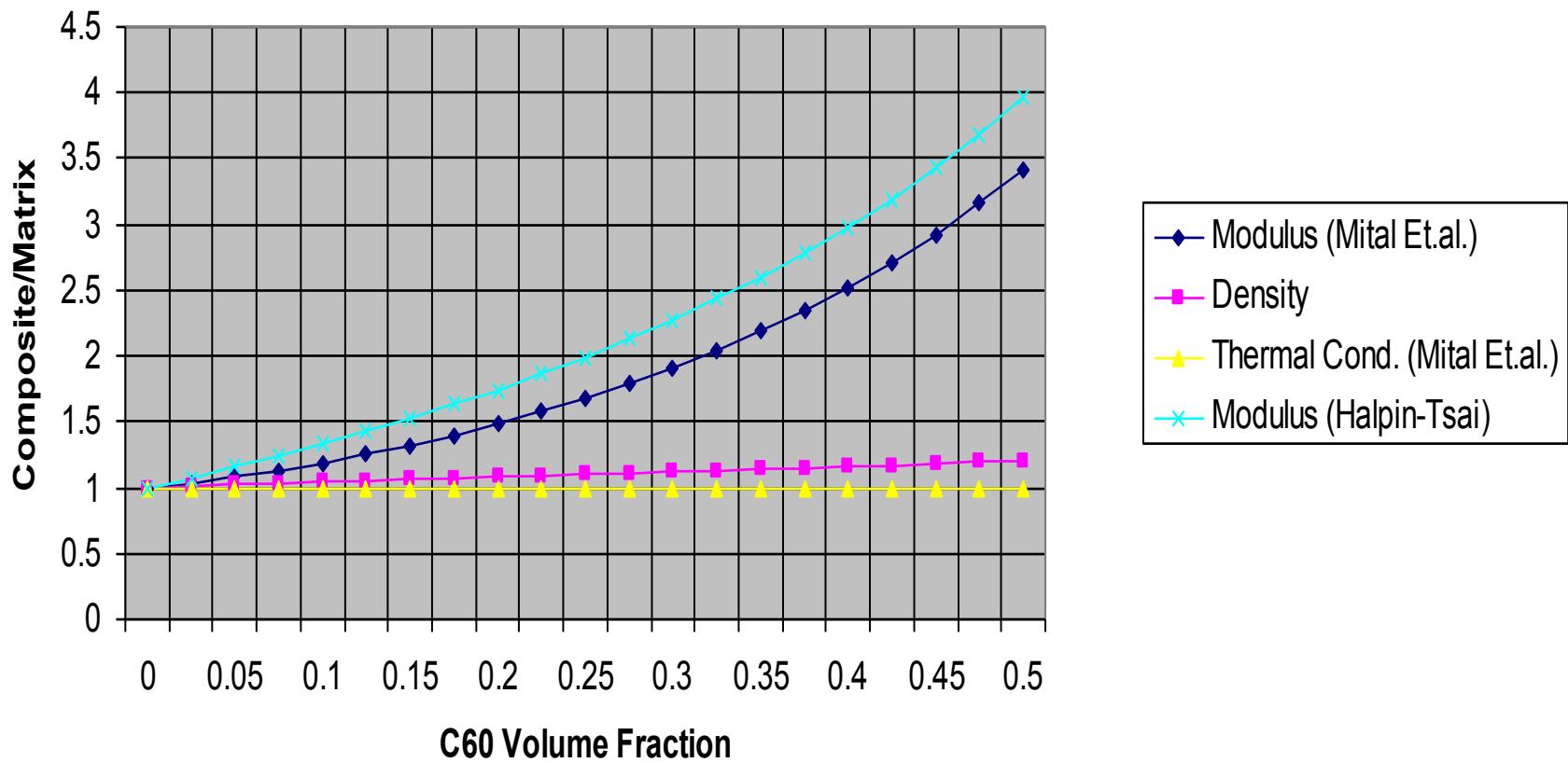


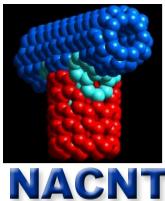


Fullerene/Epoxy Composite for High Strength-Insulating Layer



Composite Spherical Shell -ABS+C60 ($E_f=860 \text{ GPa}$, $E_m=1.8 \text{ GPa}$, $K_f=0.25 \text{ W/m-k}$, $K_m=0.25 \text{ W/m-k}$, $d_f=1.745 \text{ g/cc}$, and $d_m=1.05 \text{ g/cc}$)





Models for Continuous Fiber Reinforced Composites

IC Finegan et. al., Composite Science and Tech (2003)

Halpin-Tsai Equations

$$\frac{E}{E_m} = \frac{1 + \xi \eta V_f}{1 - \eta V_f} \quad \text{where} \quad \eta = \frac{(E_f / E_m) - 1}{(E_f / E_m) + \xi}$$

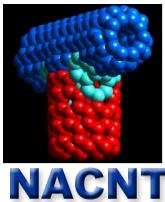
where ξ is a measure of fiber reinforcement depends on fiber geometry, packing geometry, and loading conditions at the interface

with $\xi = 2l/d$ for longitudinal modes and $= 2$ for transverse modes

For limiting cases, the measure of fiber reinforcement could be 0 (series model) or infinity (parallel model).



Tensile Strength for Discontinuous Fiber Composites



Critical length for discontinuous composite

$$l_c = \frac{\sigma_f d}{\tau_c}$$

where τ_c Is the shear strength of the bond at the interface

and σ_f is the tensile strength

$$TS_{comp} = TS_f V_f \left(1 - \frac{l_c}{2l}\right) + TS_m (1 - V_f) \quad \text{for} \quad l > l_c$$

$$TS_{comp} = \left(\frac{l \tau_c}{d}\right) V_f + TS_m (1 - V_f) \quad \text{for} \quad l < l_c$$



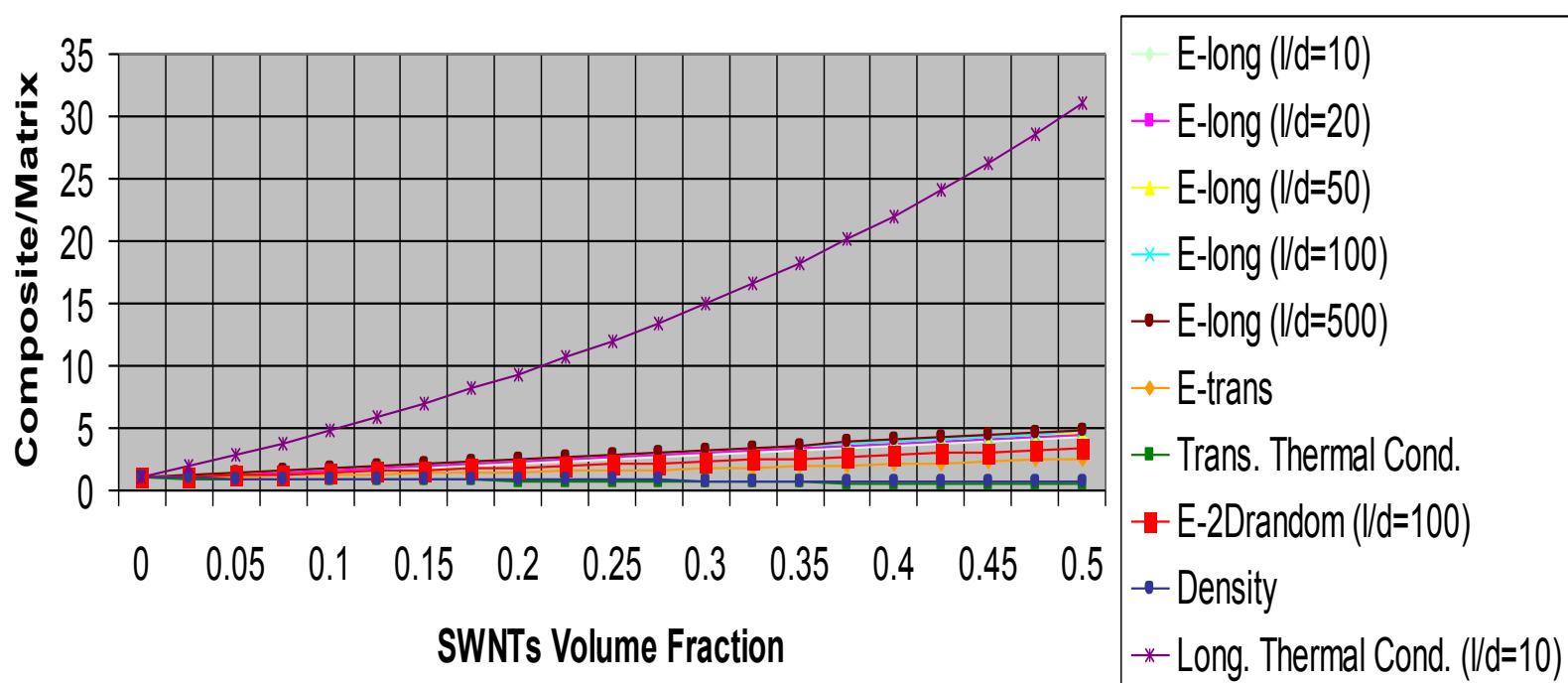
Ti + SWNT Composites: Thermal/Mechanical



Composite Spherical Shell -Ti+SWNTs

Based on Halpin-Tsai Equations

($E_{\text{long}}=1000 \text{ GPa}$, $F_{\text{trans}}=860$, $E_m=116 \text{ GPa}$, $K_{fl}=2000 \text{ W/m-k}$, $K_{ft}=0.25 \text{ W/m-k}$, $K_m=17 \text{ W/m-k}$, $d_f=1.745 \text{ g/cc}$, and $d_m=4.5 \text{ g/cc}$)





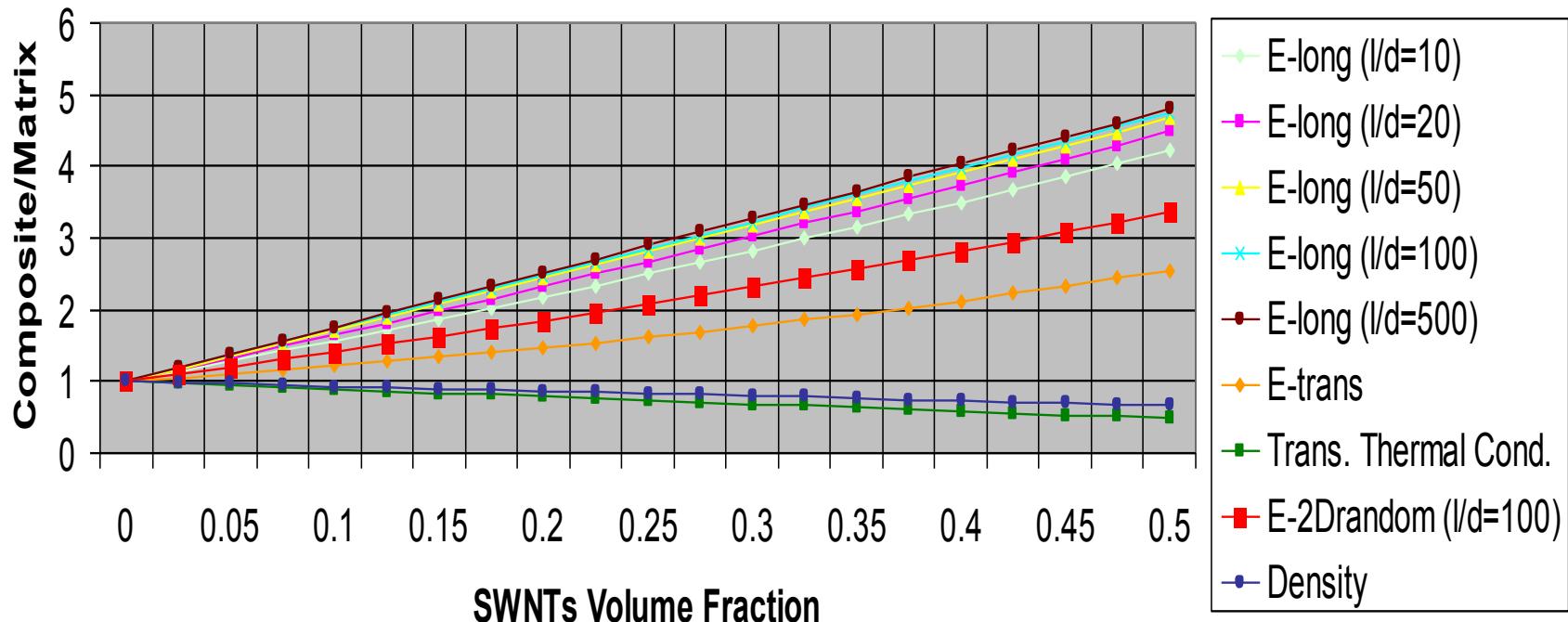
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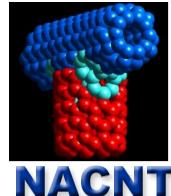
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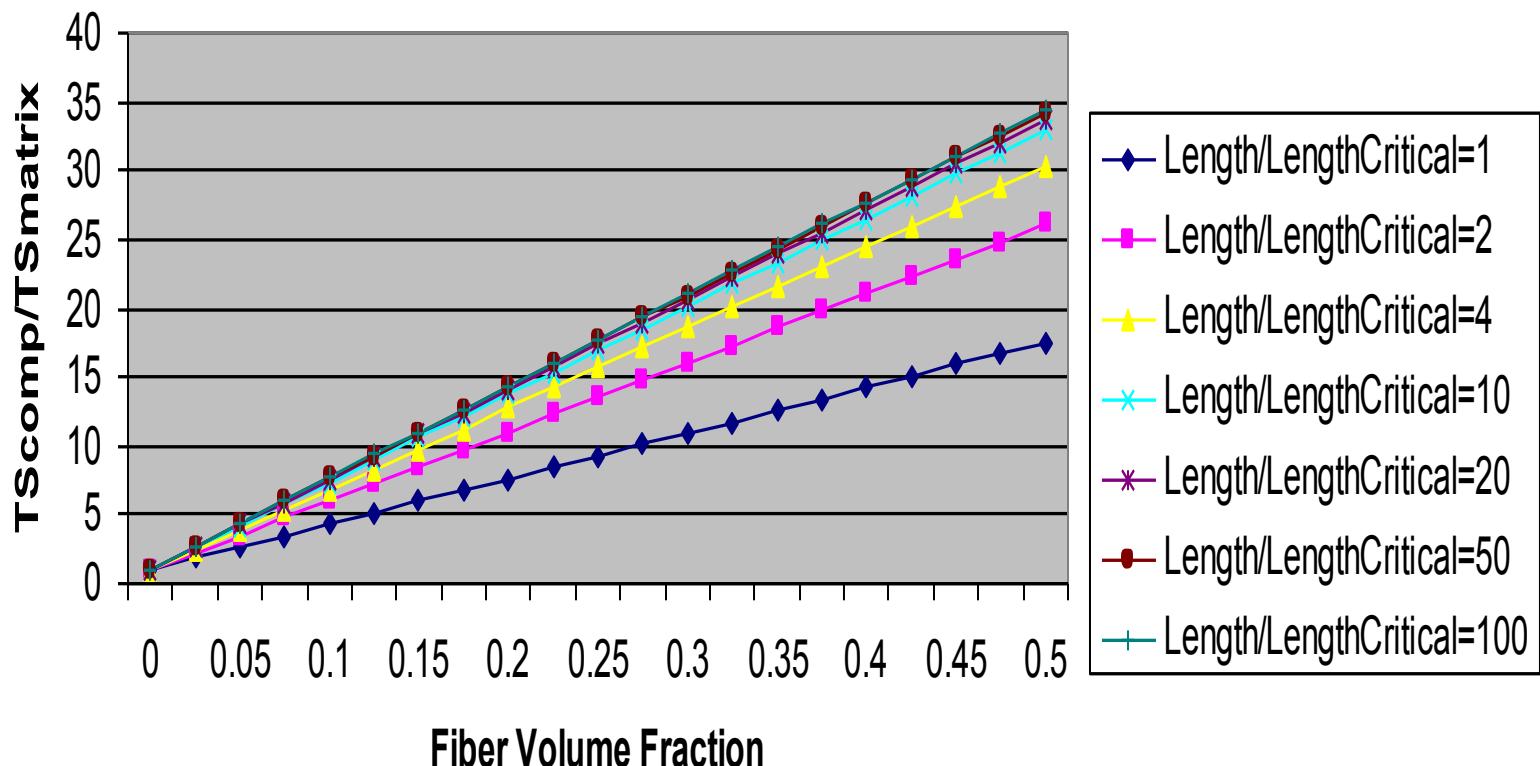




Ti + SWNT Composites: Tensile Strength

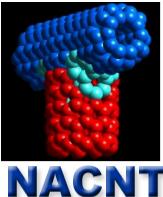


Longitudinal Tensile Strength (TS) of Nanotube-Titanium Composite for L>Lc ($TS_f=15\text{GPa}$ and $TS_m=220 \text{ MPa}$)

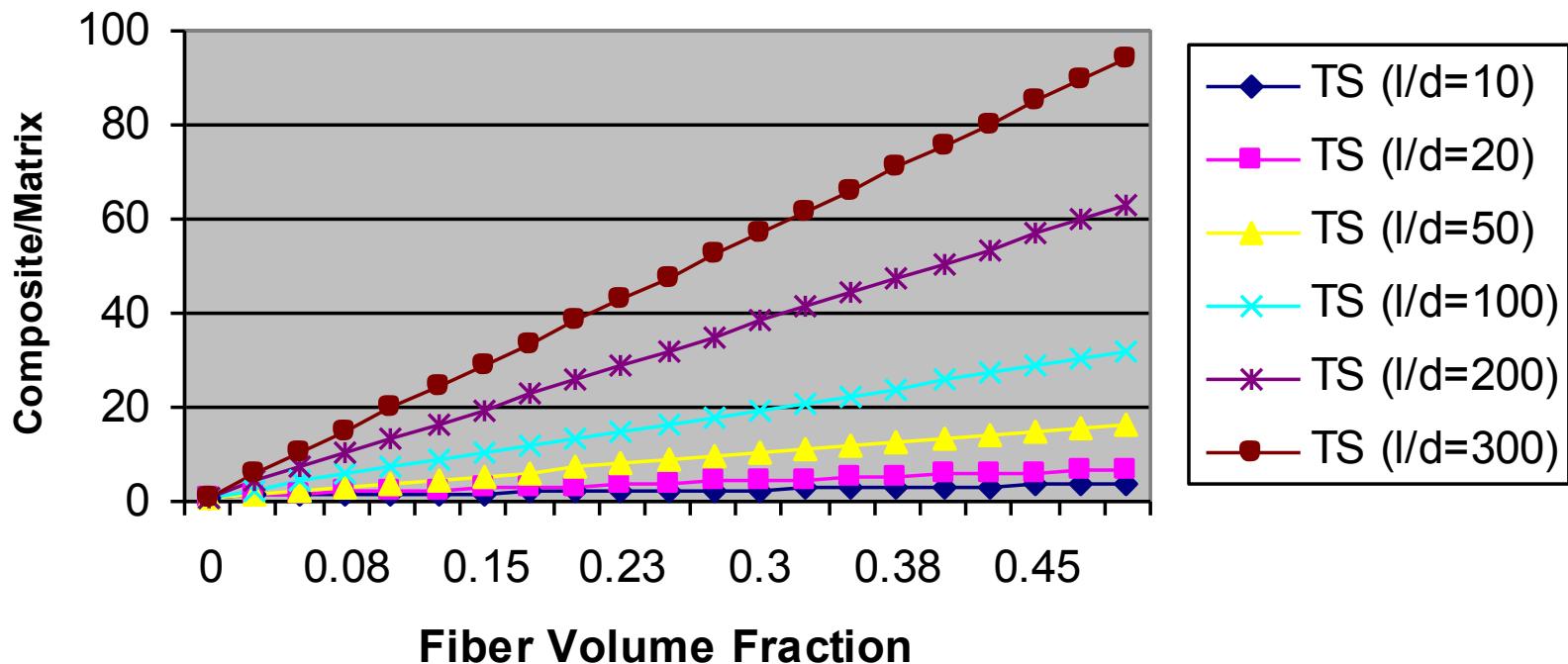




Ti + SWNT Composites: Tensile Strength

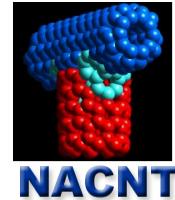


Tensile Strength (TS) of Nanotube-Polymer Composite. Results for Polymer with TS of 80 MPa and Bond Shear Strength of 50 MPa ($L < L_c$)

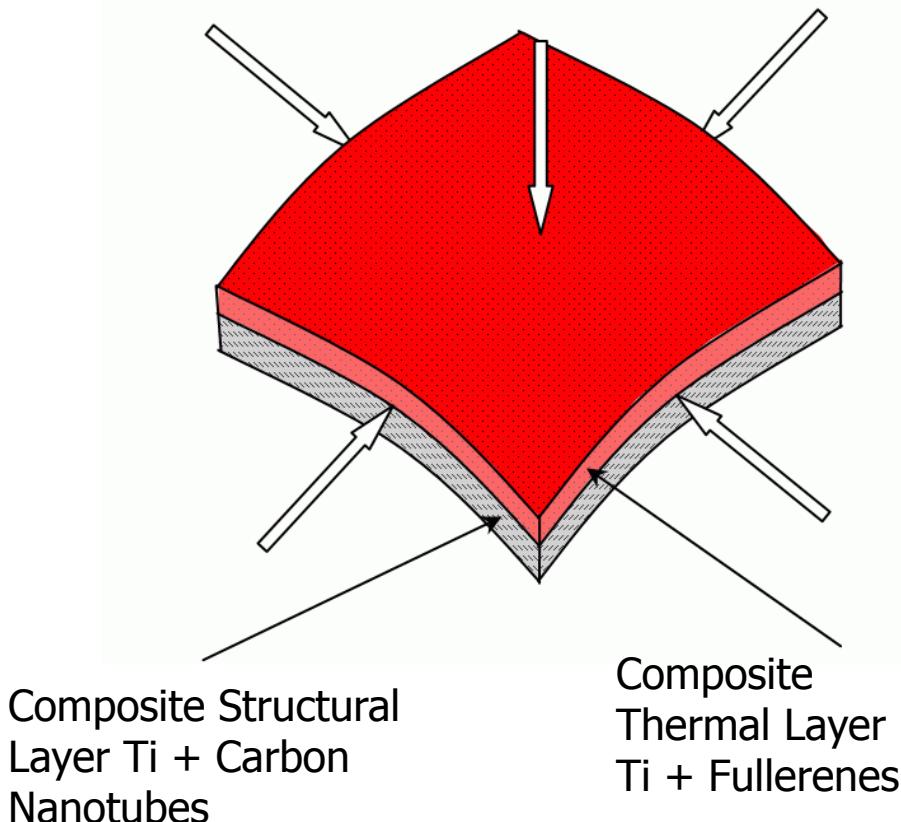




Nano-structured Shell for Pressure Vessels



Nano-enabled Spherical Shell Compressional Loading and Temperature



- 0.35 Fullerene / 0.65 Ti Composite Modulus (+100%)
Density (-25%)
Th Cond. (-50%)
- 0.35 CNT / 0.65 Ti Composite Modulus (+250%)
Density (-25%)
Th Cond (L) ($\times 15-20$)
Th Cond (T) ($\times 0.75$)
Tensile S ($\times 20$ $L > L_c$)
Tensile S ($\times 40$ $L < L_c$)
- These are upper-limits for stiffness and thermal conductivity estimates:
Assumption: micro-mechanical models with mostly perfect interfaces